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A criterion for cracking during solidification

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Abstract—Cracking during solidification is a serious defect in castings and welds. When solidification shrinkage and thermal contraction of the semisolid and its surrounding solid are obstructed, tensile deformation can be induced in the semisolid to cause cracking along grain boundaries that are not fed with sufficient liquid. A criterion for cracking was derived, focusing on events occurring at the grain boundary including separation of grains from each other, lateral growth of grains toward each other, and liquid feeding between grains. An index for the susceptibility of an alloy to cracking during solidification was also proposed, that is, $|dT/d(f_S{}^{1/2})|$ near $(f_S)^{1/2} = 1$, where T is temperature and f_S the fraction solid in the semisolid. The index affects: (a) the lateral growth rate of two neighboring grains toward each other to bond together to resist cracking, and (b) the length of the grain-boundary liquid channel through which feeding has to occur to resist cracking. The index was verified with experimental data in casting and welding of Al alloys.

Keywords: Solidification cracking; Hot tearing; Aluminum alloys; Welding; Casting

1. Introduction

Alloys are susceptible to cracking during solidification. Al alloys, stainless steels and Ni-base alloys are notable examples. In casting such cracking is called hot tearing [1,2]. In welding it is called solidification cracking [3]. Cracking occurs in the region of semisolid called the mushy zone. According to Novikov [4], cracking during solidification is caused by obstructed shrinkage. An alloy tends to shrink during solidification due to solidification shrinkage inside the mushy zone and thermal contraction both inside and outside the mushy zone. Solidification shrinkage is caused by the higher density of the solid than the liquid, e.g., by 6.6% in the case of Al [1]. Thermal contraction, on the other hand, is associated with the thermal expansion coefficient of materials. In casting shrinkage is obstructed by the rigid mold walls, especially those of metal molds. In welding it is obstructed by the rigid body the workpiece is clamped down or connected to.

Obstructed shrinkage induces tension in the mushy zone. The mushy zone most often consists of columnar, though sometimes equiaxed, dendritic grains that are separated from one another by liquid. The semisolid has little strength because the grains are not yet bonded together firmly but still separated by the grain boundary liquid. The problem is that the semisolid also has little ductility during the terminal stage of solidification when the fraction of liquid f_L is no longer high enough for the grains to move around and rearrange themselves to accommodate the tensile strain. Thus, cracking can occur along grain boundaries during terminal solidification.

Numerous models have been proposed for hot tearing in castings, and some of them have been applied to solidification cracking in welds. Several hot tearing models proposed by various researchers were reviewed, for instance, by Eskin et al. [5]. These models include the stress-based models, strain-based models and the strain rate-based models. Essentially, stress-based models assume a semisolid will crack when tensile stresses exceed their strength. Strain-based models usually assume a semisolid will crack when tensile strains are sufficient to break the grain-boundary liquid films. It has become clear more recently that the strain rate, instead of the strain itself, plays a critical role in cracking during solidification. The existence of a critical strain rate above which cracking occurs during solidification was confirmed in welding experiments by Matsuda et al. [6] and more recently by Coniglio and Cross [7].

The model of Prokhorov [8] focuses mainly on the thermomechanical factor of cracking, assuming that cracking can occur if the rate of strain accumulation with temperature drop $d\varepsilon/dT$ exceeds a critical value. The model of Feurer [9], on the other hand, focuses mainly on liquid feeding of the shrinking mushy zone. The model, in the form of an empirical formula, assumes cracking can occur if volumetric shrinkage exceeds volumetric feeding. To include tensile deformation, Nasresfahani et al. [10] revised Feurer's model into another empirical formula that includes a uniaxial contraction stress measured during casting.

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The prominent RDG model proposed by Rappaz, Drezet and Gremaud [11] considers both uniaxial tensile deformation and shrinkage feeding. Unlike empirical formulas, the model has a physically sound basis. Columnar dendritic grains growing in one direction were considered, with tensile deformation acting normal to the growth direction and liquid feeding opposite to the growth direction. The differential control volume for mass balance analysis consisted of both dendrite arms and the liquid between them. A steady-state differential mass-balance equation involving both phases was applied, following the two-phase approach of Wang et al. [12]. The equation was integrated over the mushy zone to determine the velocity distribution of the liquid in the mushy zone. The velocity was then related to Darcy's law and further integrated across the mushy zone. A void was assumed to form and give rise to a crack when the liquid pressure in the mushy zone fell below a certain cavitation pressure p_c. The maximum deformation rate $\dot{\varepsilon}_{p,\max}$ sustainable by the mushy zone before a hot tear nucleates at the root of the dendrites was determined by the following equation:

$$\int_{T_S}^{T_L} \frac{(\int f_S \dot{\varepsilon} dT)(f_S)^2}{(1-f_S)^3} dT = \frac{\lambda_2^2}{180} \frac{G}{(1+\beta)\mu}(p_m - p_c) - v_T \frac{\beta}{1+\beta} \int_{T_S}^{T_L} \frac{(f_S)^2}{(1-f_S)^2} dT \quad (1)$$

where T is temperature, T_L liquidus temperature, T_S solidus temperature, f_S fraction of solid, $\dot{\varepsilon}$ strain rate normal to the growth direction, λ_2 secondary dendrite arm spacing, G temperature gradient in the growth direction, β solidification shrinkage, μ viscosity, p_m metallostatic pressure, p_c cavitation pressure, and v_T liquidus-isotherm velocity. The hot cracking susceptibility (HCS) was assumed to be proportional to $1/\dot{\varepsilon}_{p,\max}$. A plot of HCS vs. the Cu contents of binary Al–Cu alloys was shown to exhibit a Λ-shaped curve with a peak HCS near 1.4 wt.% Cu. The RDG model was used by Drezet et al. [13] to study the solidification cracking of some Al alloys. Their HCS values were calculated and compared with each other. The fraction solid f_S was calculated as a function of temperature T using a thermodynamic software package called ProPhase.

Coniglio and Cross [7] studied Al arc welds with the RDG model and demonstrated that cavitation in the mushy zone due to pressure drop is not likely to occur. Instead, a porosity-based crack initiation model was proposed. A crack growth model was also proposed to relate the crack growth rate to the local strain rate through mass balance.

The scope of the present study is similar to that of the RDG model [11]. It covers columnar dendritic grains growing in one direction, subjected to tensile deformation normal to the growth direction and liquid feeding opposite to the growth direction. However, the approach is different. Instead of dealing with the mushy zone as a whole as in the RDG model, it focuses on the events occurring at the grain boundary, including the separation of the grains from each other by tensile deformation, growth of the grains toward each other due to solidification, and feeding of liquid along the grain boundary due to shrinkage. The purpose of the present study is not to predict if cracking will actually occur during solidification, but to shed light on predicting the crack susceptibility of an alloy.

2. Criterion for cracking

2.1. Linking radius of columnar dendritic grains with fraction solid

Consider the growth of columnar dendritic grains illustrated in Fig. 1. Let ϕ be the grain spacing, that is, the distance between the axis of a one grain and that of its neighboring grain. For simplicity, the grains are assumed to grow in the z-direction within hexagons of a characteristic radius $\phi/2$ and a transverse cross-sectional area A. The outer contours of the transverse cross-sections of the grains are initially round but become increasingly hexagonal as solidification proceeds. The characteristic radius and the transverse cross-sectional area of the grains are l and a, respectively.

Liquid is present both between the grains and inside them at various locations between dendrite arms. The former affects cracking during solidification but not the latter. The volume fraction of all liquid is f_L and that of solid f_S. For simplicity the density difference between the solid and liquid phases is tentatively neglected at this point. It is assumed that porosity, if it is present, is in the form micro-sized pores with negligible volume. Thus, $f_S + f_L = 1$. Since the grains are columnar, the area ratio a/A at a given location z can be considered as the effective volume fraction of solid f_{SE} at z, that is, $f_{SE} = a/A$. Furthermore, $f_{SE} = f_S + f_{LD}$, where f_{LD} is the volume fraction of the liquid inside the grains at z. Since f_{LD} is a portion of f_L, it can expressed as $f_{LD} = \alpha f_L$, where $0 < \alpha < 1$. Thus,

$$f_{SE} = f_S + f_{LD} = f_S + \alpha f_L = f_S + \alpha(1 - f_S) = \alpha + (1 - \alpha) f_S \quad (2)$$

During terminal solidification, $f_S \to 1$ and $\alpha(1 - f_S) \ll f_S$. For instance, if $f_S = 0.9$ and $\alpha = 0.2$ then $\alpha(1 - f_S) = 0.2 \times 0.1 = 0.02 \ll 0.9$. So,

$$[f_{SE}]_{f_S \to 1} = [f_S + \alpha(1 - f_S)]_{f_S \to 1} \cong [f_S]_{f_S \to 1} \quad (3)$$

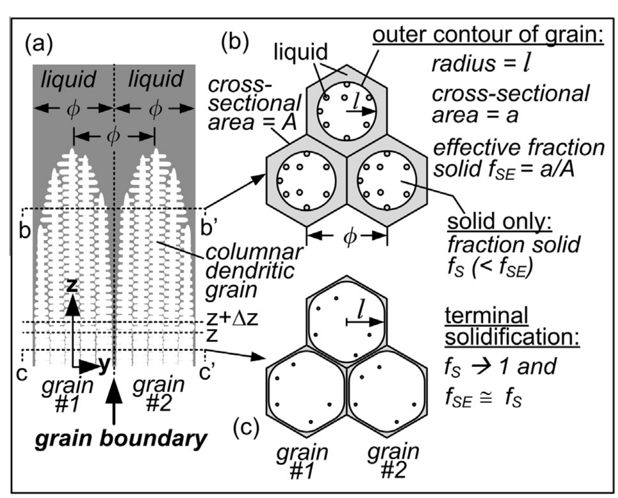

Fig. 1. Growth of columnar dendritic grains: (a) longitudinal cross-section; (b) transverse cross-section at bb′ in (a); (c) transverse cross-section at cc′ in (a) ϕ is grain spacing.